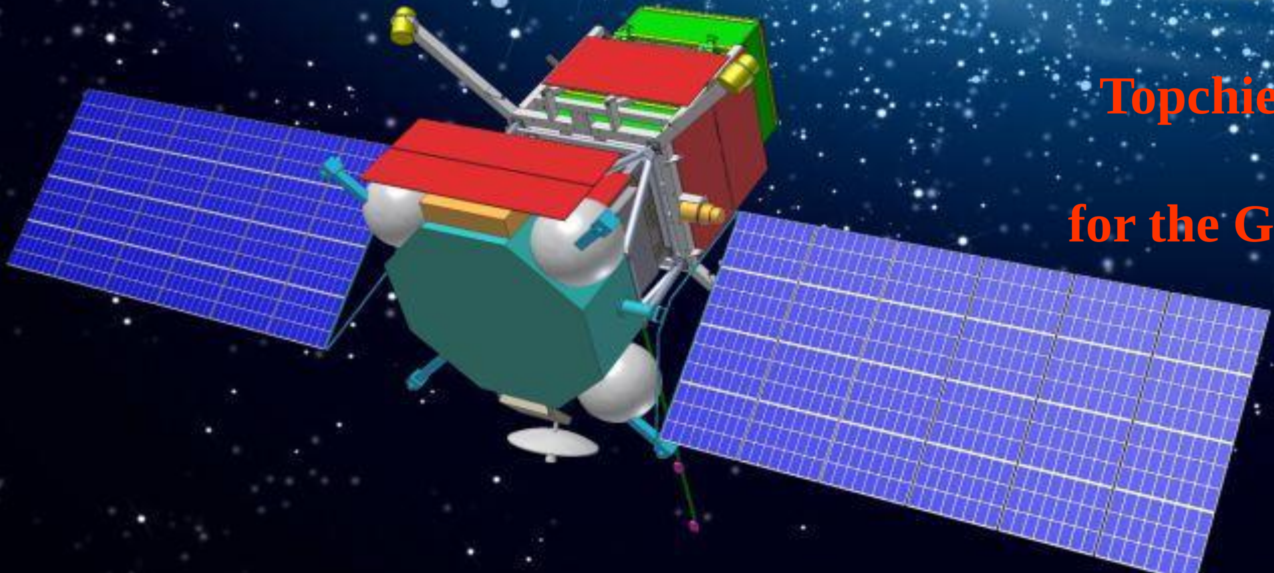
Russian Academy of Sciences
P.N.Lebedev Physical Institute
LPI

Cosmophysical research with GAMMA-400

MEPhI
National Research Nuclear University • Moscow Engineering Physics Institute • MEPhI



Topchiev Nikolay (substitution by Leonov Alexey)
for the GAMMA-400 collaboration

ICPAA-2022, Moscow, November 29, 2022

Gamma-ray astronomy in Soviet Union and Russia

Ginzburg V L, Syrovatskii S I
"Some problems of gamma and X-ray astronomy" *Sov. Phys. Usp.* **7** 696–720 (1965)

Ginzburg V L, Syrovatskii S I "Origin of cosmic rays" *Sov. Phys. Usp.* **9** 223–235 (1966)

Gal'per A M, Kirillov-Ugryumov V G, Luchkov B I, Prilutskii O F
"The study of cosmic γ rays" *Sov. Phys. Usp.* **14** 630–654 (1972)

Gal'per A M, Kirillov-Ugryumov V G, Luchkov B I
"Observational gamma astronomy" *Sov. Phys. Usp.* **17** 186–198 (1974)

Gal'per A M, Kirillov-Ugryumov V G, Luchkov B I
"Discrete Sources of Cosmic Gamma Radiation" *Sov. Phys. Usp.* **20** 350–351 (1977)

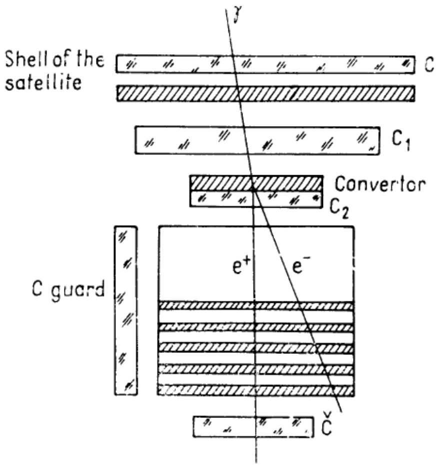
Gal'per A M, Luchkov B I, Prilutskii O F
"Gamma rays and the structure of the Galaxy" *Sov. Phys. Usp.* **22** 456–473 (1979)

Gal'per A M, Kotov Yu D, Luchkov B I
"The diffuse cosmic gamma radiation" *Sov. Phys. Usp.* **23** 873–874 (1980)

Gamma-ray astronomy in Soviet Union and Russia

Cosmos-251 (1968) and 264 (1969)

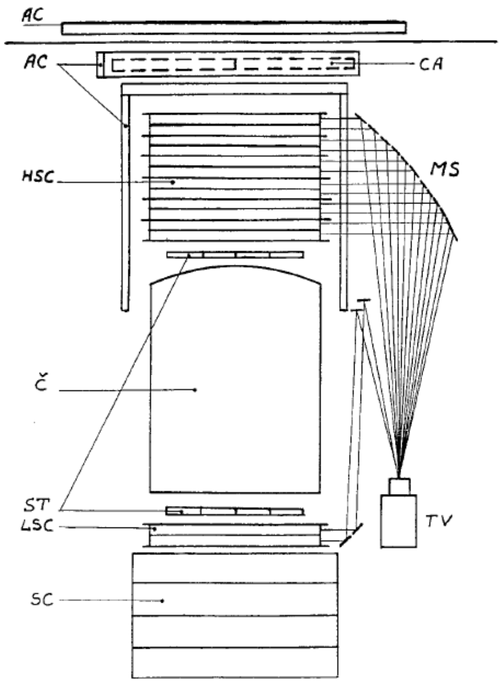
MEPhI and IKI
A. Galper et al.



E_γ=100-1500 MeV

GAMMA-1 (1990-1992)

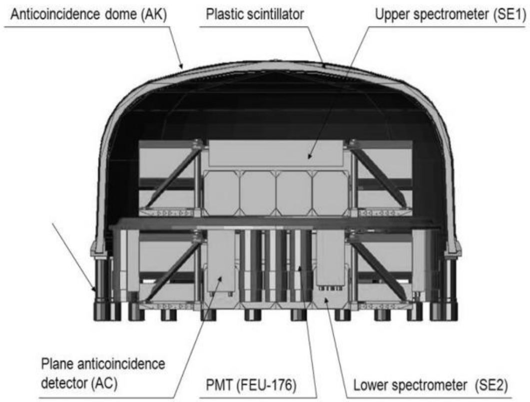
MEPhI, IKI, LPI et al.
A. Galper et al.



E_γ=50-5000 MeV

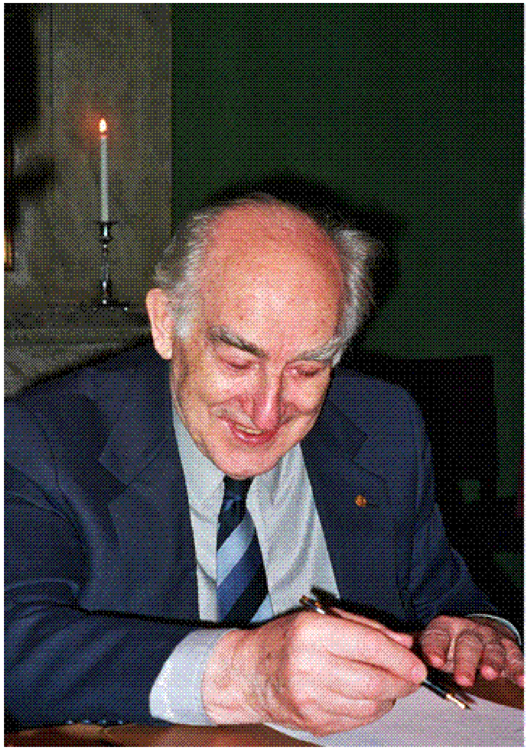
Coronas-Photon (2009)

MEPhI and LPI
Yu. Kotov et al.



E_γ=0.3-2000 MeV

GAMMA-400 gamma-ray observatory



V.L. Ginzburg

L.V. Kurnosova

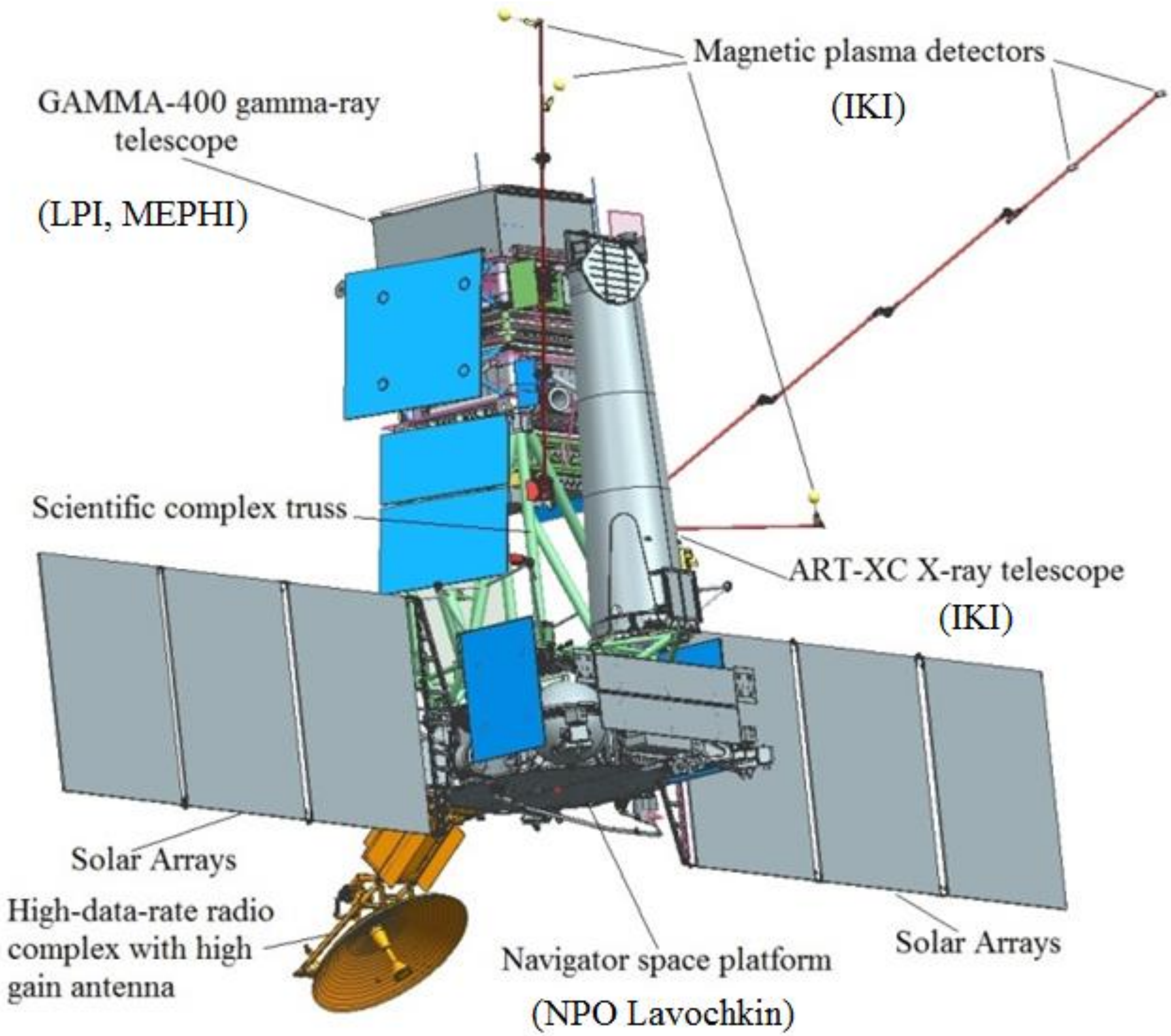
AM. Galper

The founders of the GAMMA-400 project were
Academician V.L. Ginzburg (LPI) and Professor L.V. Kurnosova (LPI).
Since 2009, the principal investigator of GAMMA-400 is
Professor MEPhI A.M. Galper.

GAMMA-400 gamma-ray observatory project

The GAMMA-400 space complex, which includes the space observatory for the study of high-energy gamma-ray emission, is being developed in accordance with the Federal Space Programs of the Russian Federation for 2009-2015 and 2016-2025

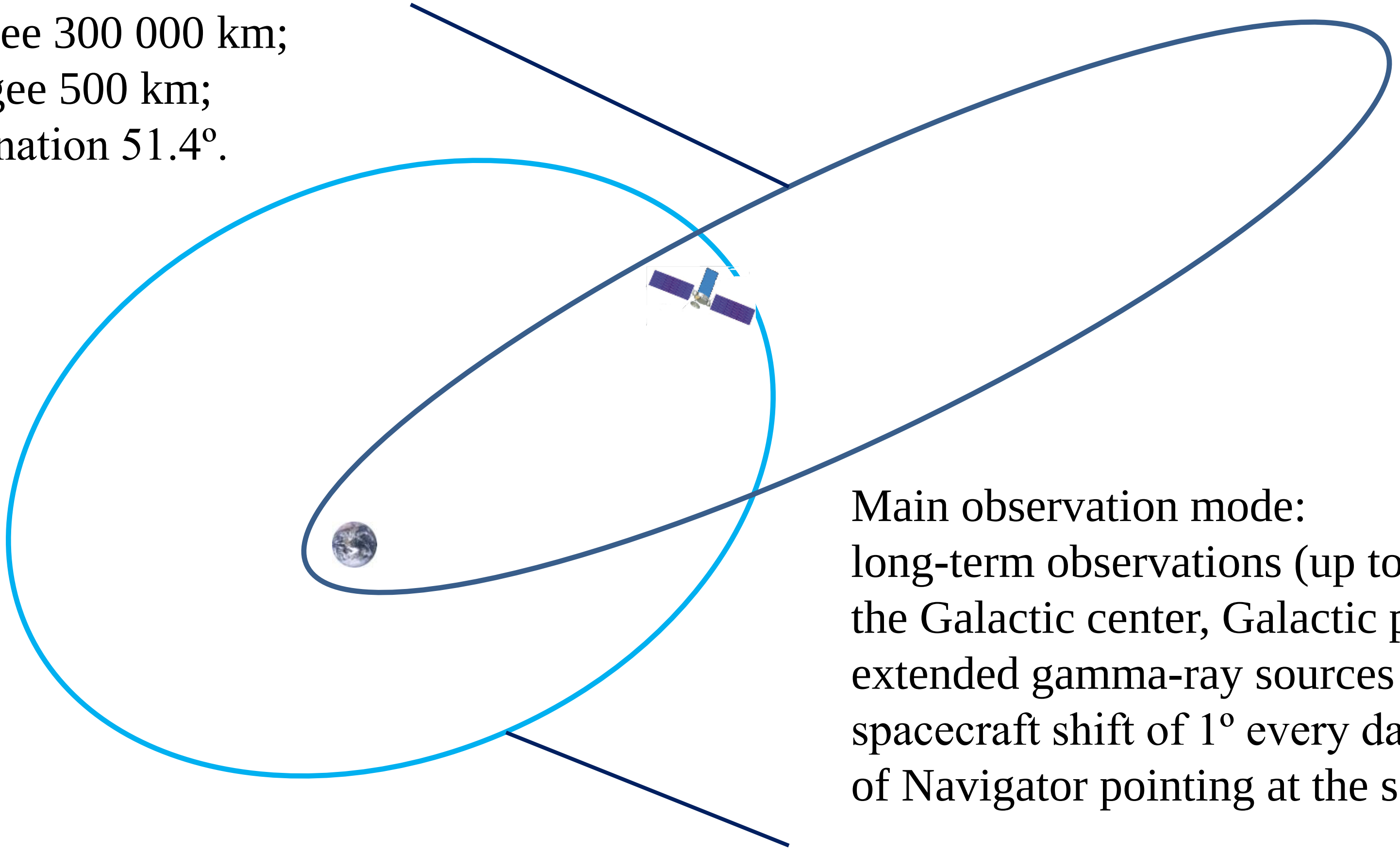
The view of the GAMMA-400 gamma-ray observatory



The GAMMA-400 gamma-ray telescope and additional scientific equipment: the ART-XC X-ray telescope and magnetic-plasma detectors PLAZMA-400. GAMMA-400 and ART-XC telescopes are located coaxially and have fields of view of ±45° and ±0.2°, respectively. Instrument designs do not obscure each other.

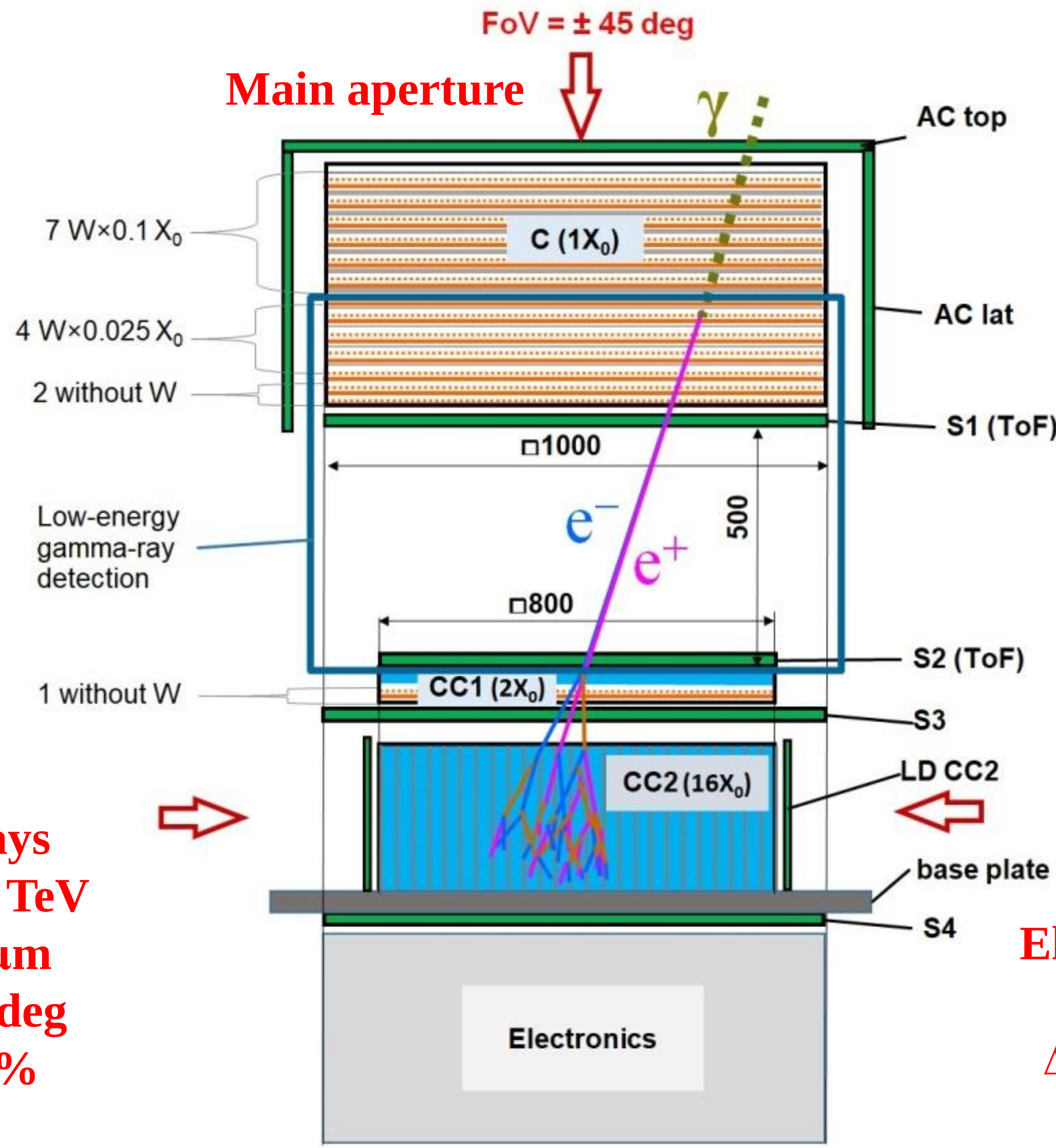
The GAMMA-400 orbit and observation mode

Orbit will be highly elliptical with initial orbit parameters:
-apogee 300 000 km;
-perigee 500 km;
-inclination 51.4º.



Main observation mode:
long-term observations (up to 100 days) of the Galactic center, Galactic plane and extended gamma-ray sources with a spacecraft shift of 1º every day. Accuracy of Navigator pointing at the source is 30″.

Under the influence of the Sun, Moon and Earth, in about 6 months, the orbit will completely go out of radiation belts and will become circular with a radius of ~150 000 km. Thus, the orbit will be outside the radiation belts and will not be obscured by the Earth.



Gamma rays
20 MeV - ~1 TeV
$\Delta x,y$ = 60 μm
$\Delta\theta$ = ~0.01 deg
$\Delta E/E$= ~2%
18 X_0

Electrons + positrons
10 GeV – ~20 TeV
$\Delta E/E$= ~2% (<1%)
18 X_0 (43 X_0)

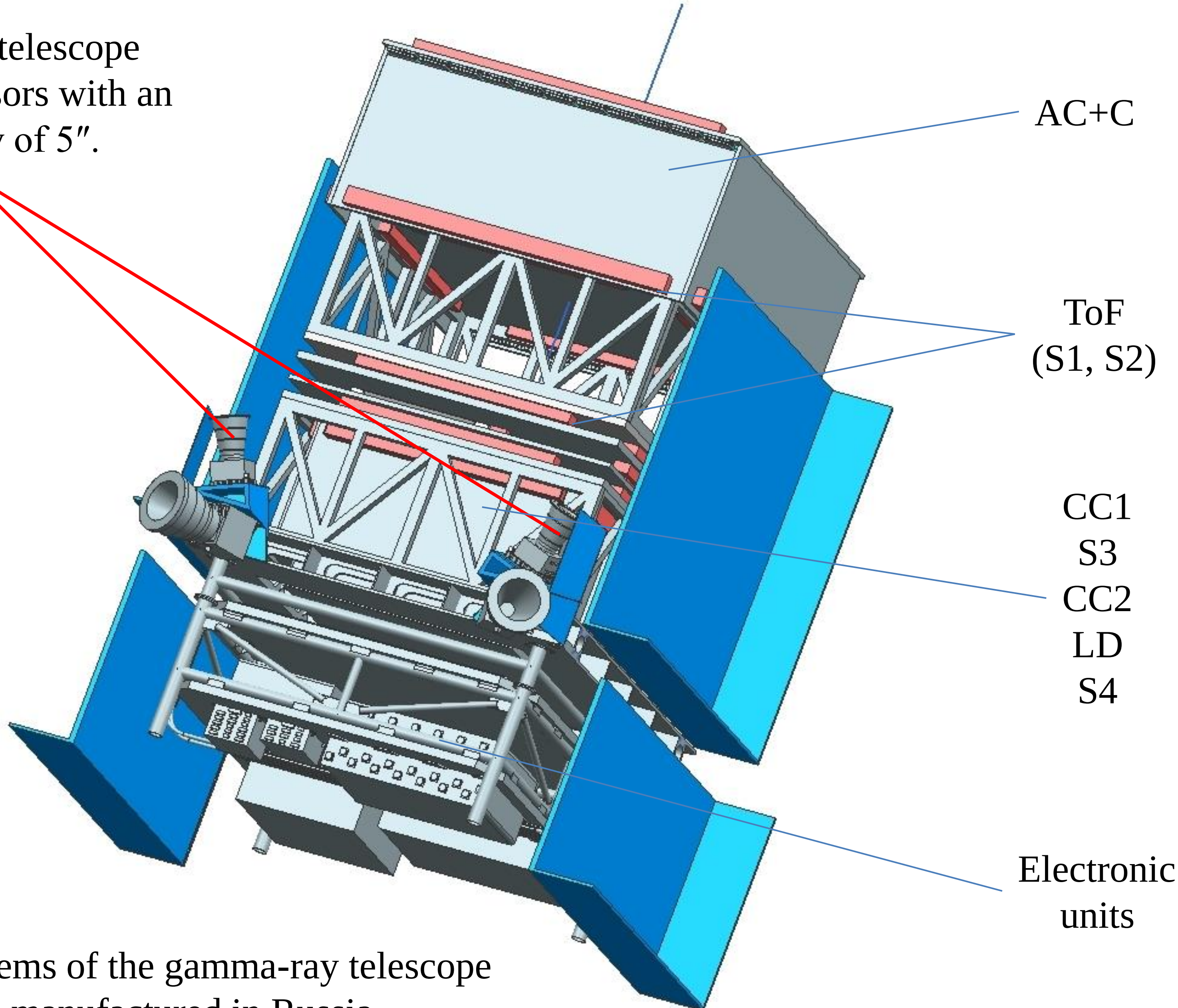
Physical scheme of the GAMMA-400 gamma-ray telescope

AC, S1, S2, S3, S4, LD are plastic scintillation detectors, C consists from SciFi scintillation fiber detectors,

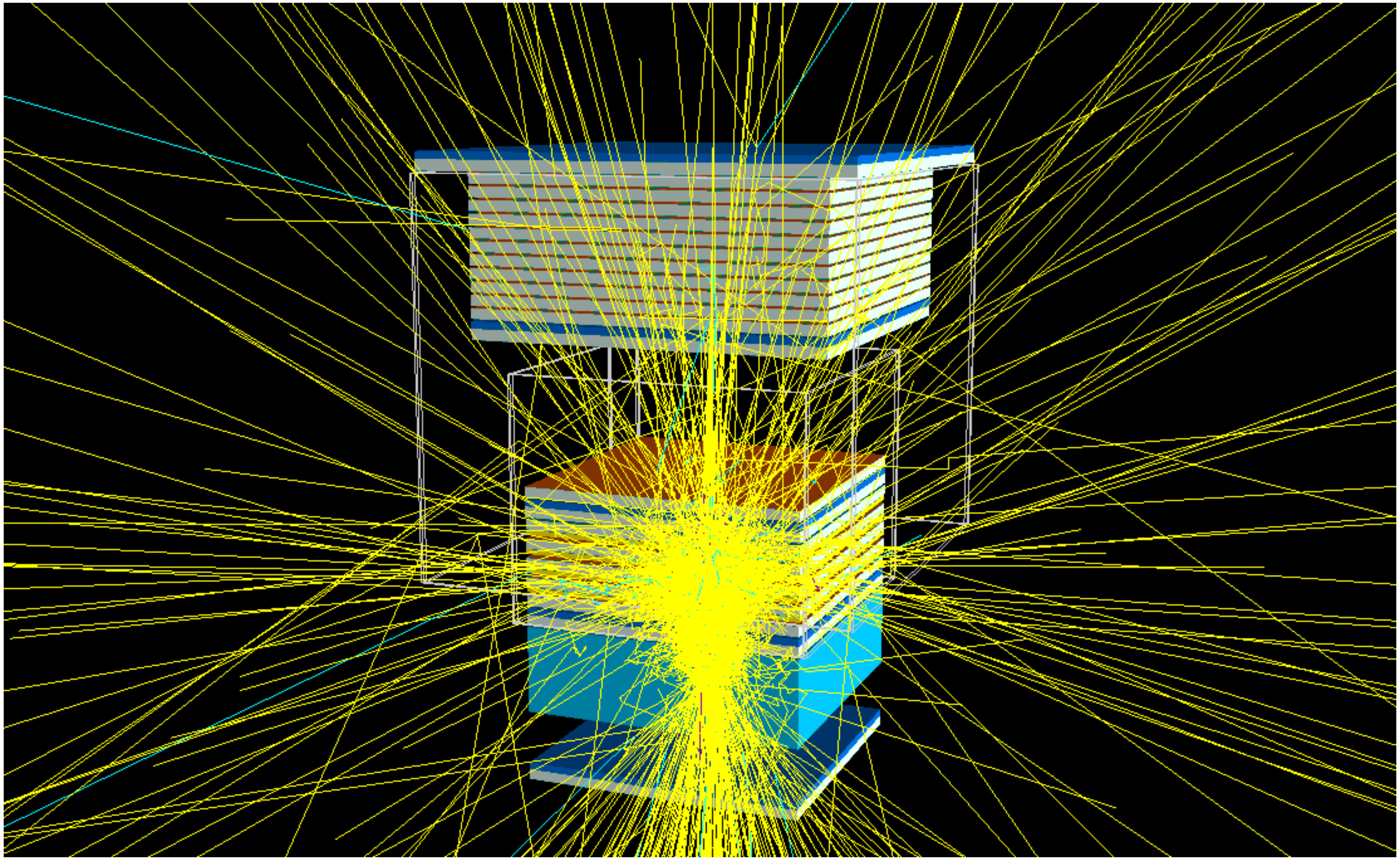
CC1 and CC2 are CsI(Tl) scintillation detectors. All detector systems have been tested.

The view of the GAMMA-400 gamma-ray telescope

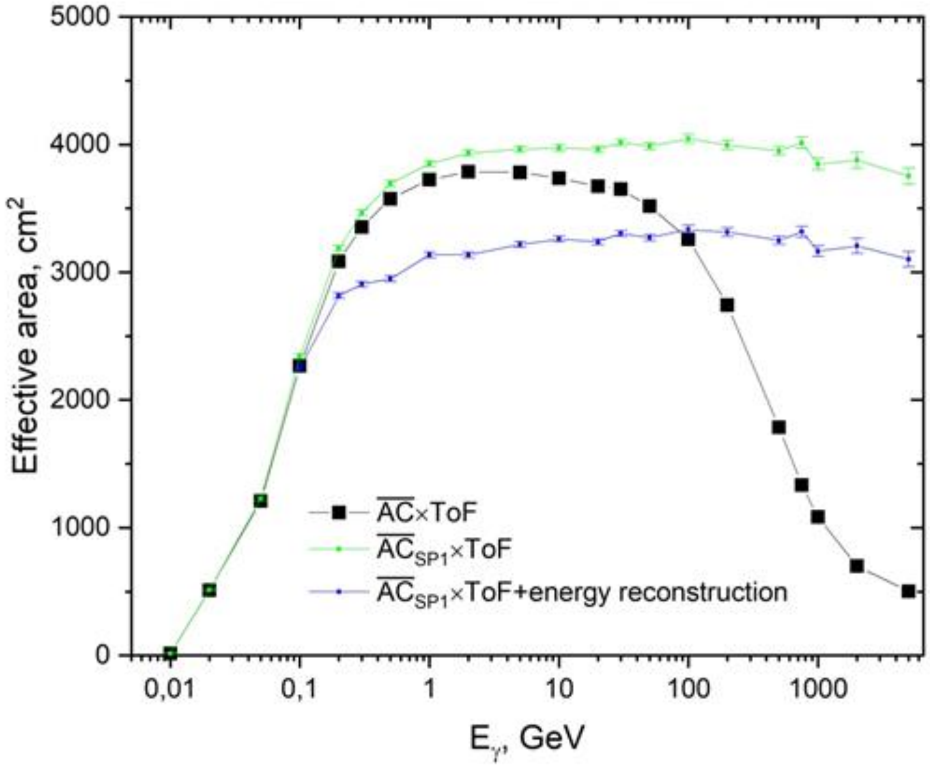
The gamma-ray telescope has two star sensors with an angular accuracy of 5″.



All detector systems of the gamma-ray telescope are designed and manufactured in Russia.



Interaction of gamma ray (E_γ = 100 GeV) with the matter of the GAMMA-400 gamma-ray telescope with the formation of backscattering particles, which can produce veto in AC and exclude primary gamma rays. To eliminate backscattering particles the methods of segmentation (all scintillation detectors are from two layers and 100-mm strips) and time of flight are used.



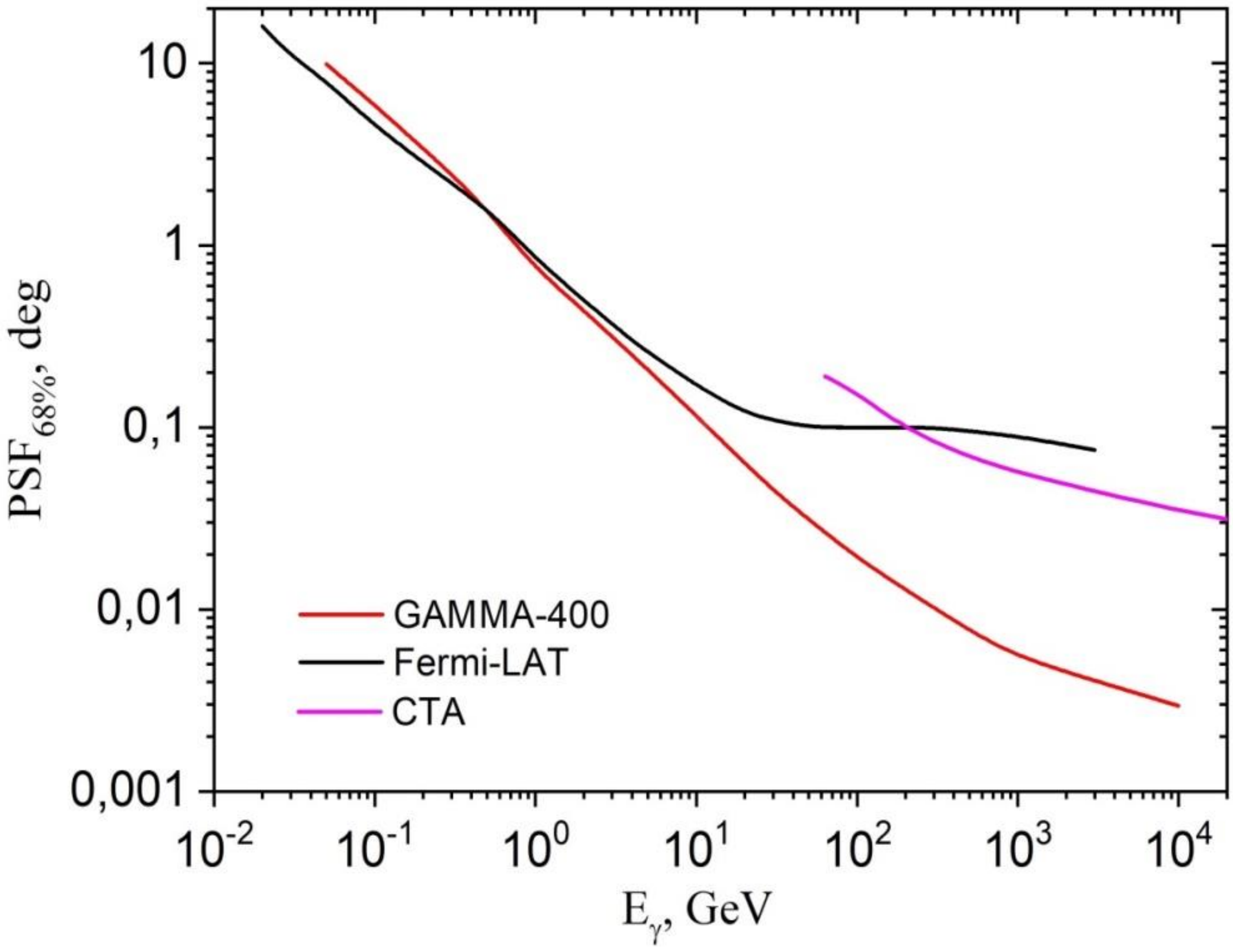
Dependence of the effective area vs energy.

Main trigger: $\overline{AC_{SP1}} \times ToF$

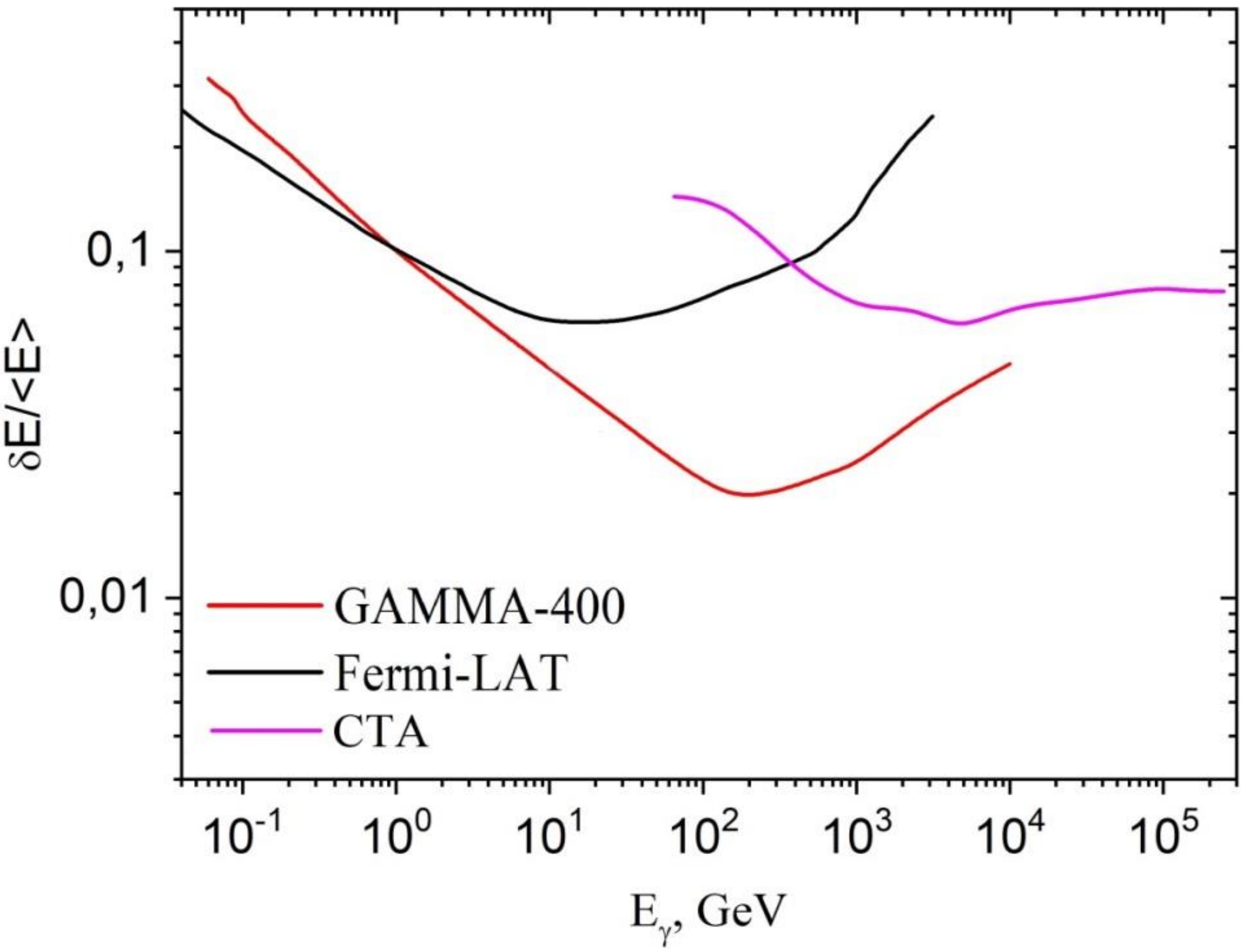
$$\overline{AC_{SP1}} = \overline{AC(same\ position\ strip)} \mid [\text{timeAC} > \text{timeS1}]$$

$$ToF = \text{S1} \times \text{S2} \times [\text{timeS1} < \text{timeS2}]$$

When recovery of track and energy are taken into account, the effective area is reduced to 3200 cm^2

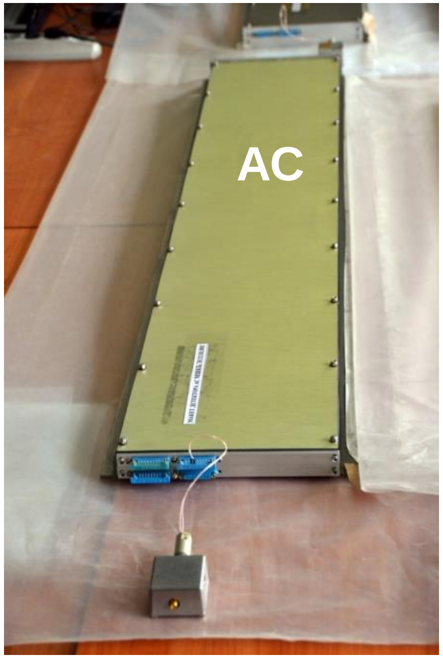


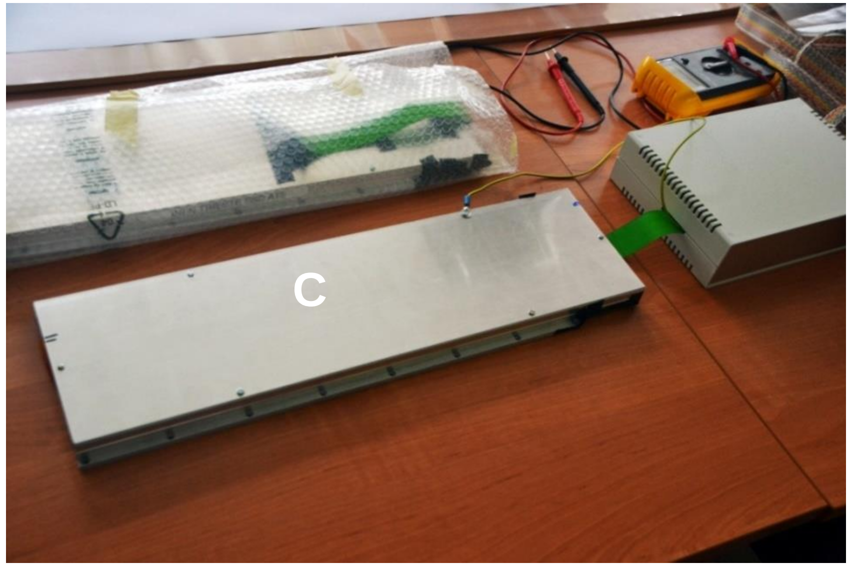
Dependence of angular resolution vs energy.

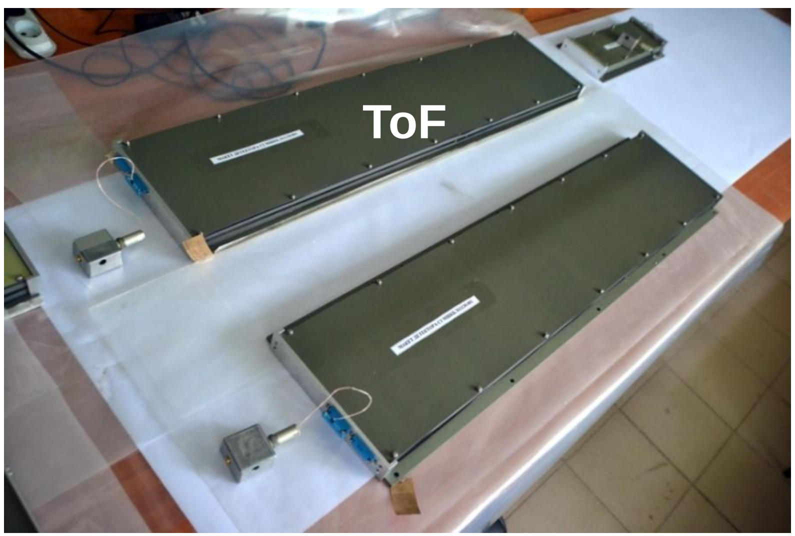


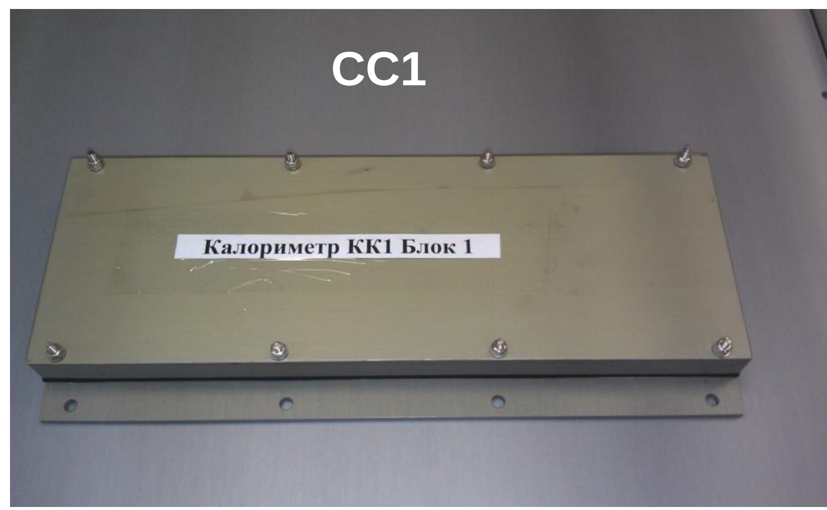
Dependence of energy resolution vs energy.

Prototypes of the GAMMA-400 detector systems



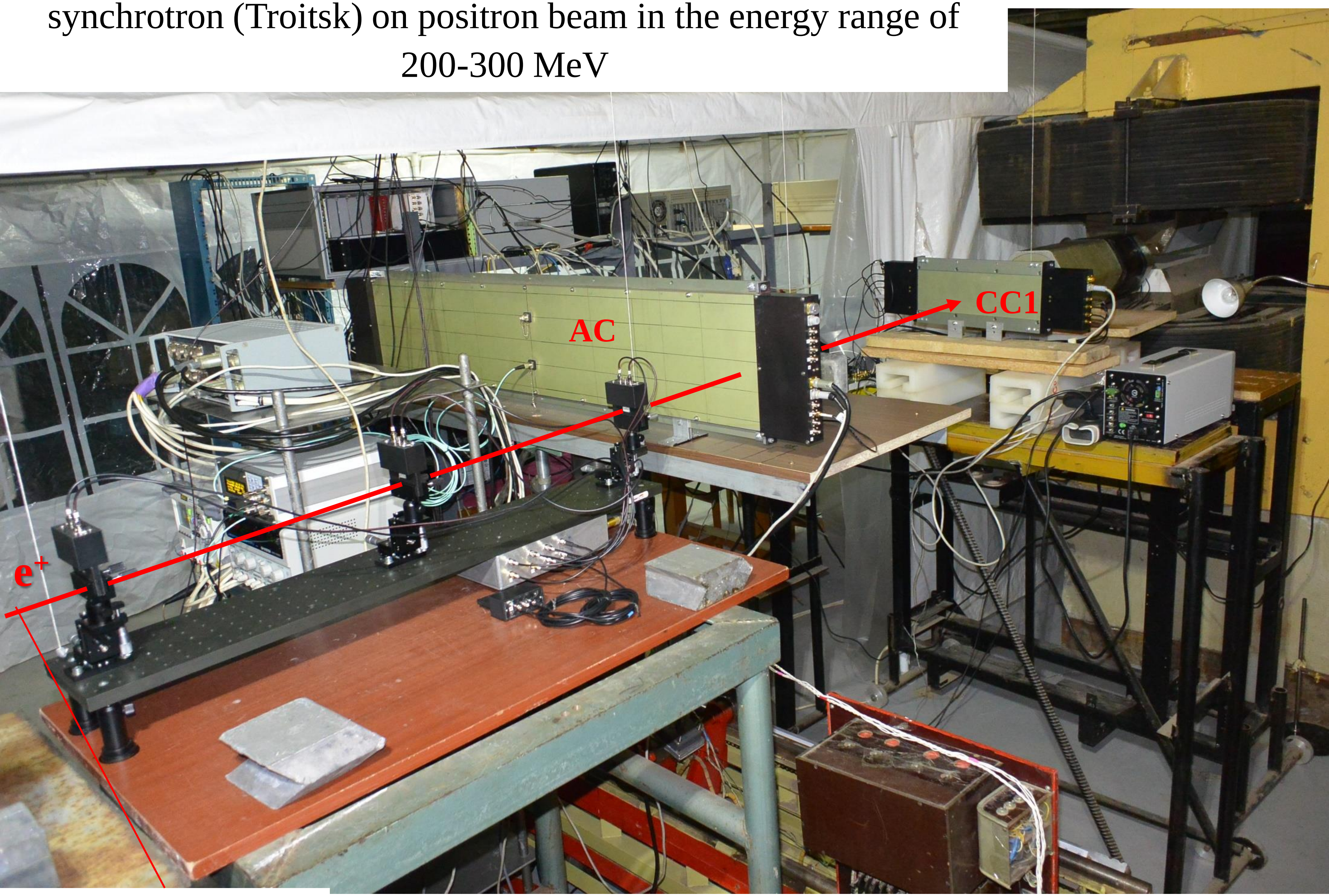




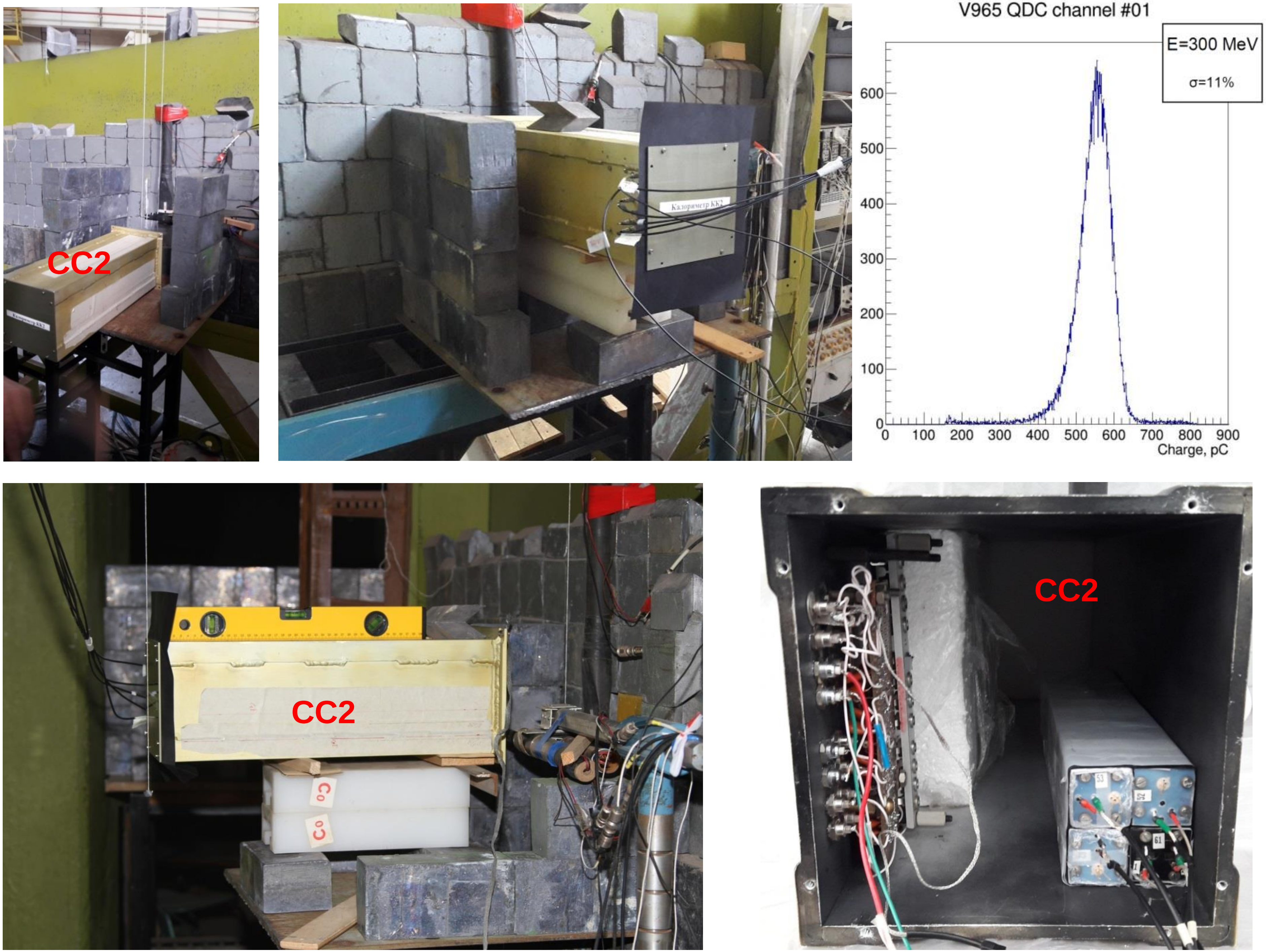


Control and measuring equipment for calibration at the LPI synchrotron (Troitsk) on a positron beam in the energy range of 200-300 MeV

Calibration of the GAMMA-400 detector prototypes at the LPI synchrotron (Troitsk) on positron beam in the energy range of 200-300 MeV



Positron beam


CC2
V965 QDC channel #01
E=300 MeV
σ=11%
0 100 200 300 400 500 600
0 100 200 300 400 500 600 700 800 900
Charge, pC
CC2
Co
Co
CC2

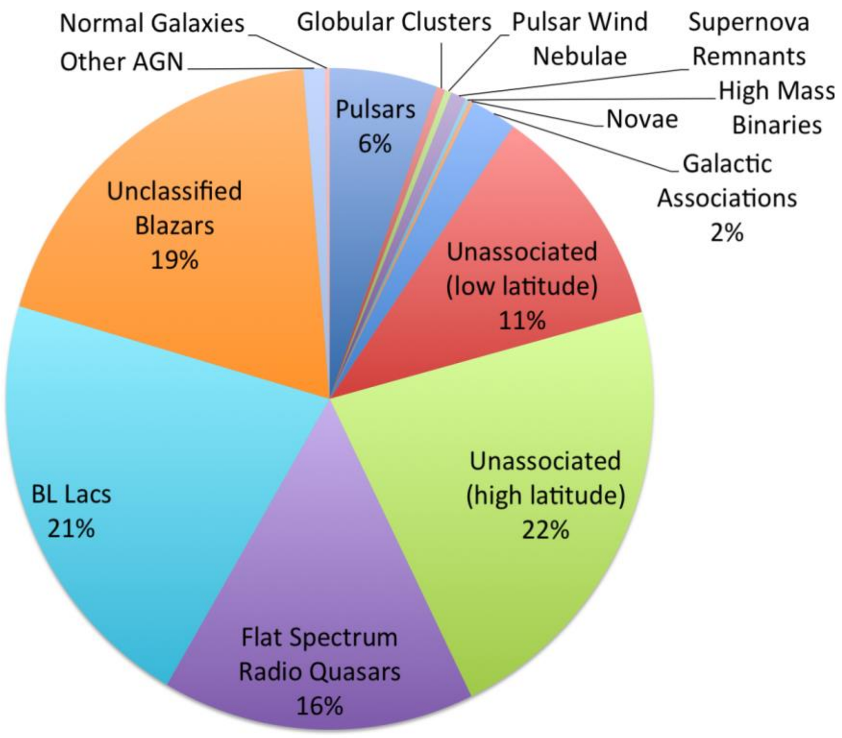
As a result of tests (2017-2022) on beam of positrons with energies of 200-300 MeV at the S-25R accelerator (LPI, Troitsk), the following characteristics were obtained:

-efficiency of detection of charged particles for AC is **0.9996**;
-time resolution for AC is **200 ps**;
-particle separation factor for ToF for particles flying up-down from down-up is **1000**;
-time resolution for ToF is **200 ps**;
-energy resolution of the calorimeter CC2 is **11%**

Main scientific tasks of the GAMMA-400 gamma-ray telescope:

-measurements of high-energy gamma-ray emission (from 20 MeV to ~1000 GeV);
-searching for features in the energy spectra of high-energy gamma-ray emission, which can be associated with dark matter particles;
-studying gamma-ray emission from the Galactic center, the Galactic plane, Fermi bubbles, pulsar nebulae Crab, Vela, Geminga, the Cygnus X complex, blazars, etc.;
-studying diffuse gamma-ray emission;
-detection of gamma-ray emission from the Sun;
-detection of gamma-ray bursts;
-detection of electron + positron fluxes up to 20 TeV.

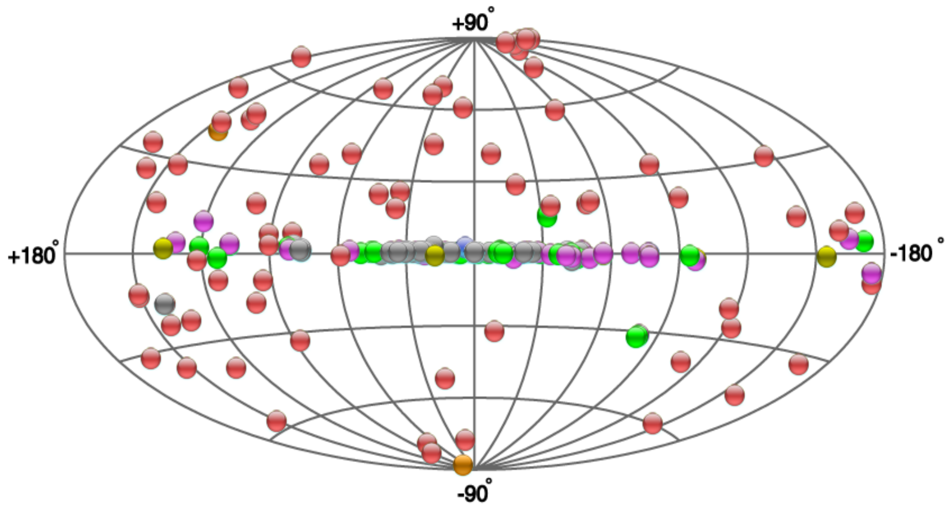
Results of gamma-ray studies from Fermi-LAT



4FGL, E_γ = 50 MeV – 1000 GeV
6658 gamma-ray sources
2157 (33%) are unidentified
(Astrophysical Journal Supplement Series, 260:53 (24pp), 2022)

Fermi-LAT angular resolution of ~0.1° (E_γ > 10 GeV) is insufficient to identify many gamma-ray sources

Results of gamma-ray emission research from ground-based gamma-ray facilities

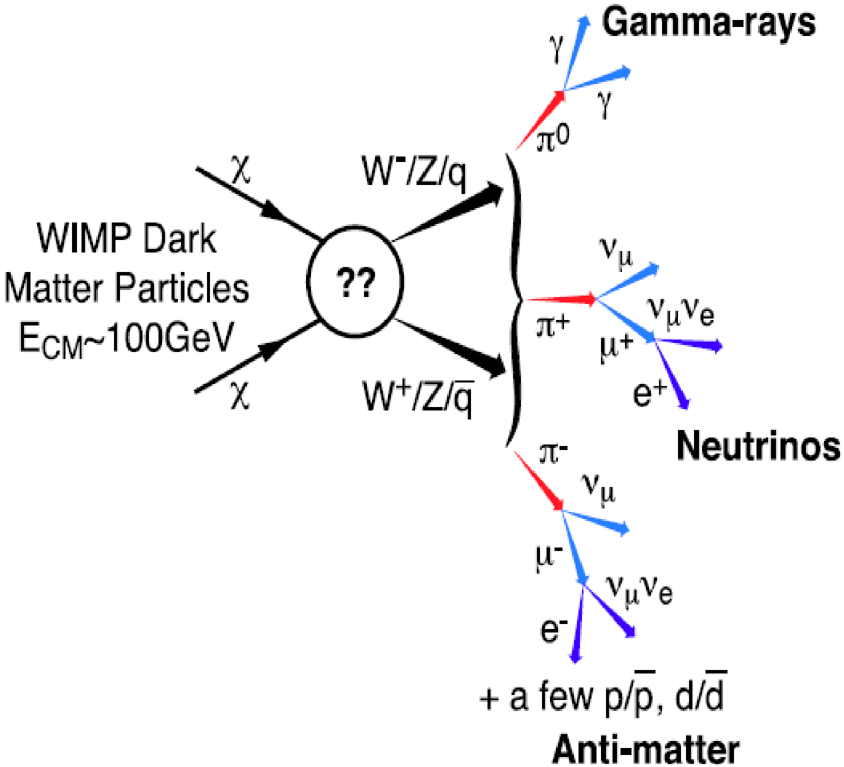


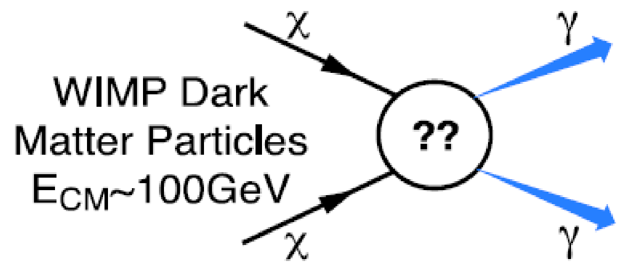
Distribution (in galactic coordinates) of ~250 discrete sources (250/6658 = 4% of Fermi-LAT sources) recorded by H.E.S.S., VERITAS, MAGIC, HAWC, LHAASO ground-based facilities for energies above 100 GeV according to the TeVCat source catalog (http://tevcat.uchicago.edu/)

The angular resolution (~0.1°, E_γ ~ 100 GeV) of ground-based facilities is insufficient to identify many gamma-ray sources

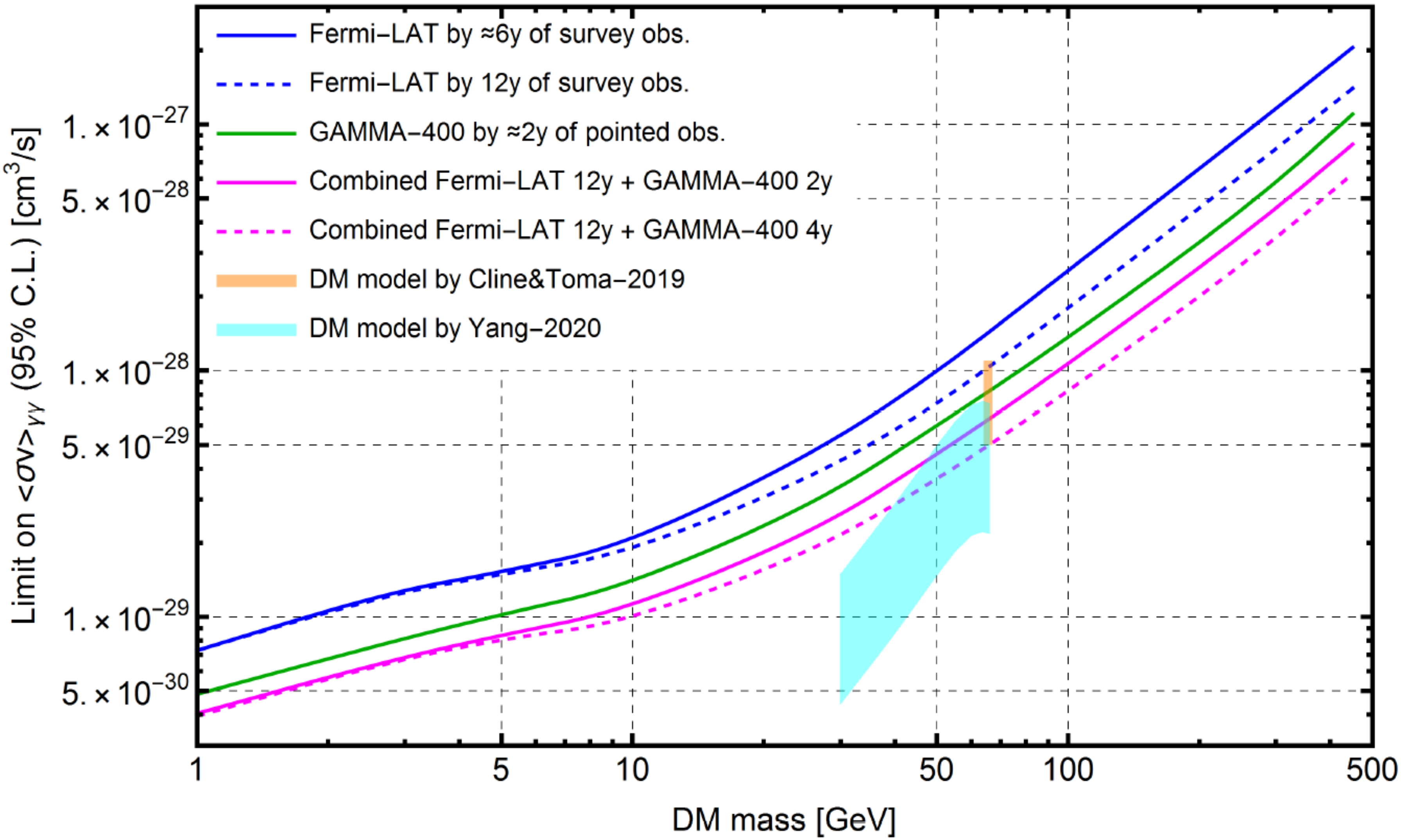
Searching for features in the energy spectra of high-energy gamma-ray emission, which can be associated with dark matter particles (WIMPs) that is, processes beyond the "Standard Model"

$$b\bar{b}, t\bar{t}, \tau^+\tau^-, \mu^+\mu^-, e^+e^-, Z^0Z^0, Z^0\gamma, W^+W^-, HH, \ldots$$

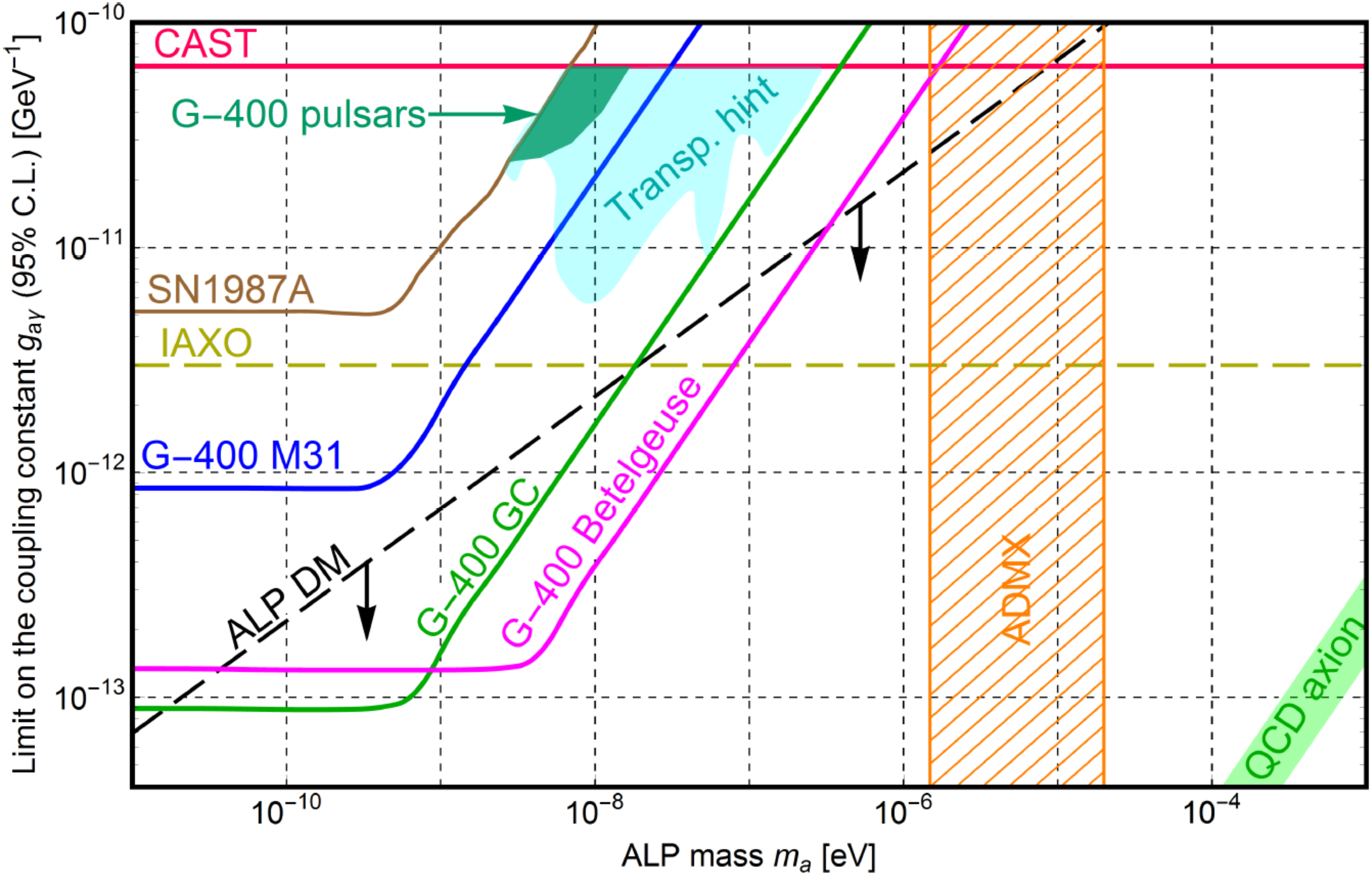




Among the huge number of possible candidates for the role of dark matter particles, supersymmetric particles, axion-like particles are considered. Weakly Interacting Massive Particles (WIMPs), whose masses can range from ~10 GeV to ~TeV, are most often considered and studied. The main task is to identify features in the energy spectra in the form of an anomalous (additional) flux or to isolate monoenergetic gamma-ray lines from the background gamma-ray emission flux.

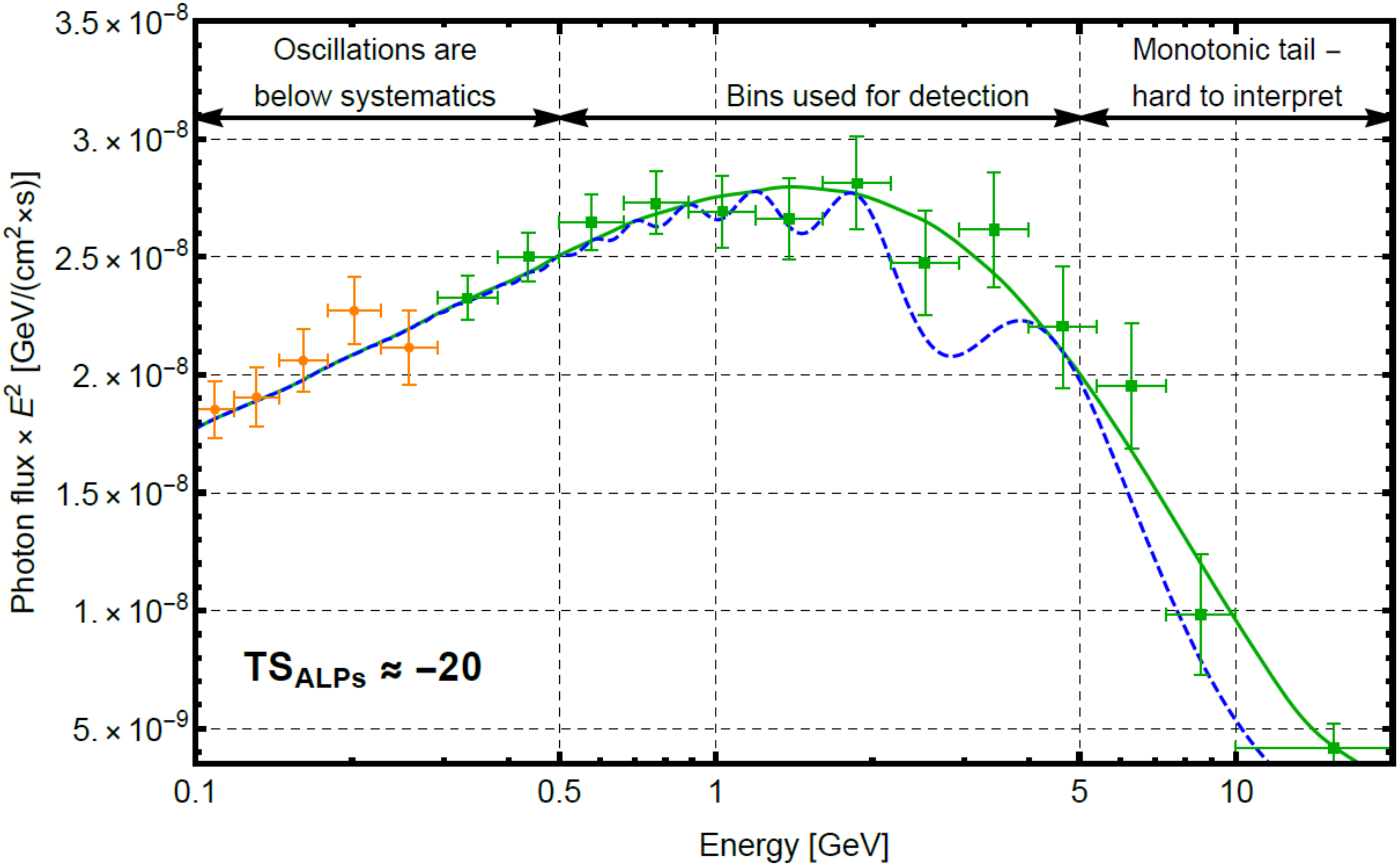


GAMMA-400 sensitivity to the diphoton annihilation cross section in comparison with that of Fermi-LAT (alone and combined) for the case of Einasto DM density prole and the ROI radius of 16^0 around the GC.



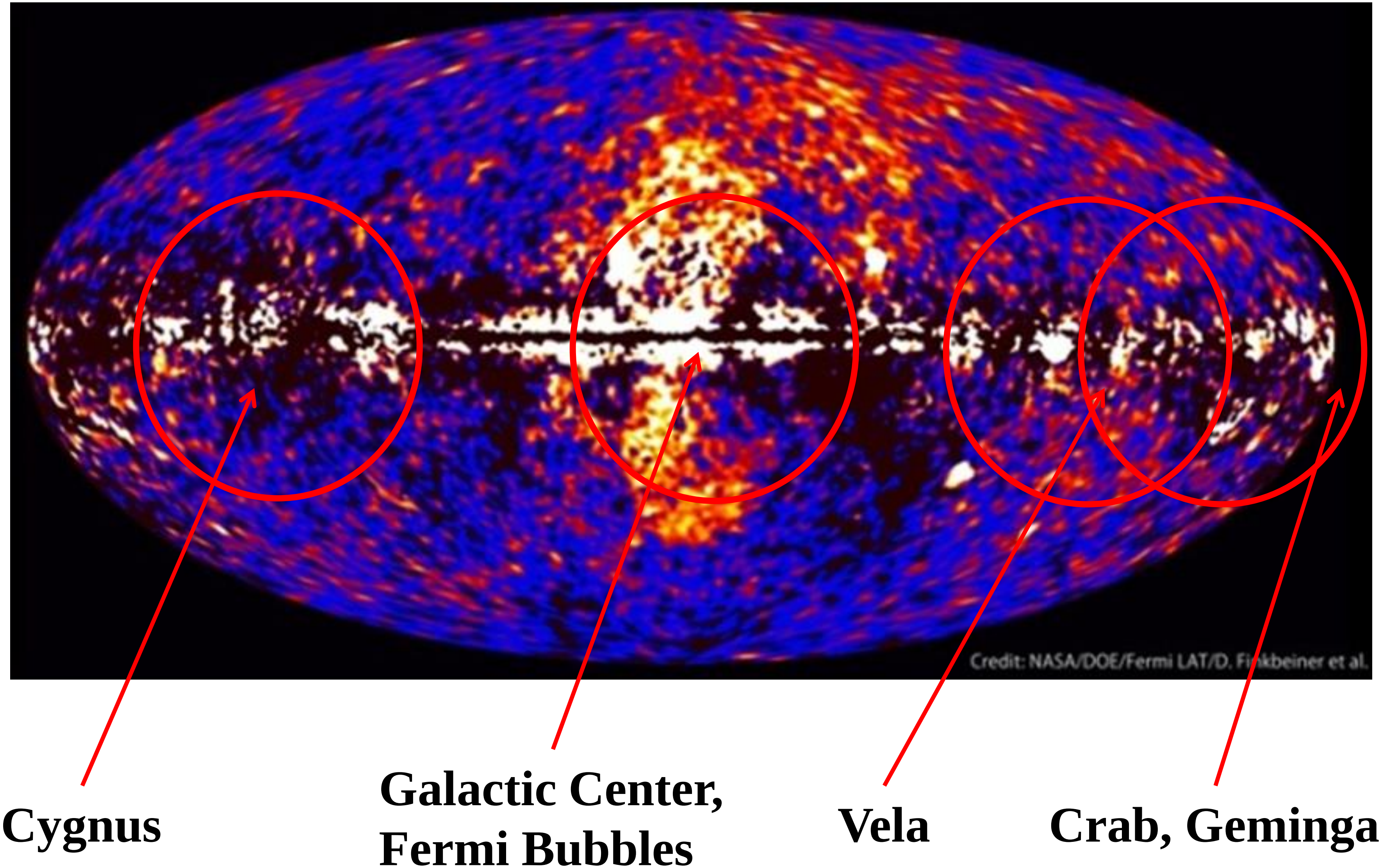
GAMMA-400 (G-400) sensitivity to the ALP-photon coupling constant by the observation of supernova in the GC, M 31 or Betelgeuse explosion. The estimation for probability of one or more SNe during 2-4 years of quasi-continuous observations is 5-9%

A. Egorov, et al., Dark matter searches by the planned gamma-ray telescope GAMMA-400, JACP11, 049, 2020

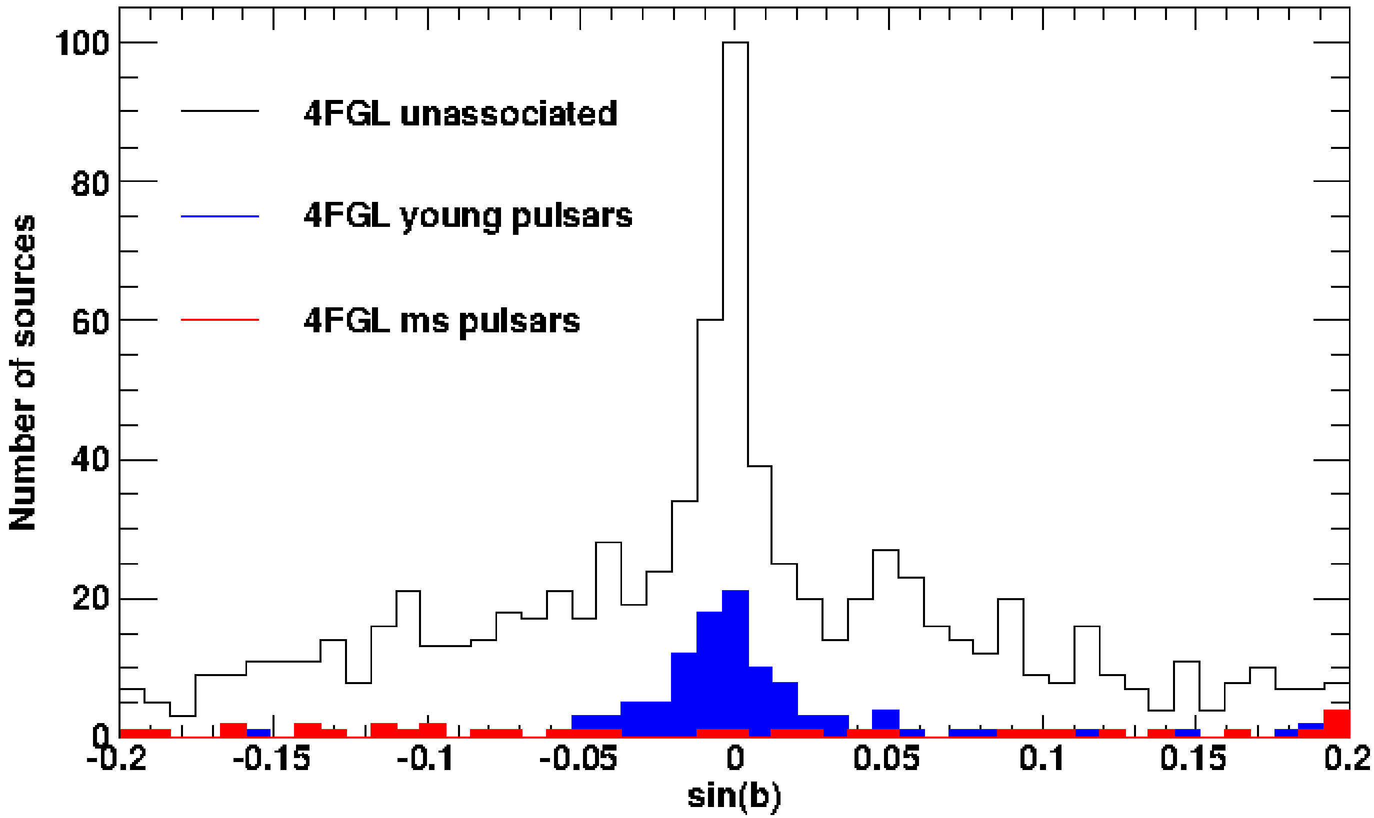


The spectra of PSR J1420-6048 with (blue dashed) and without (green) oscillations caused by ALPs (m_a = 7.0 neV, g_a = 4.6×10^{-11} GeV^{-1}) together with the simulated GAMMA-400 data points. The exposure time is 0.5 years.

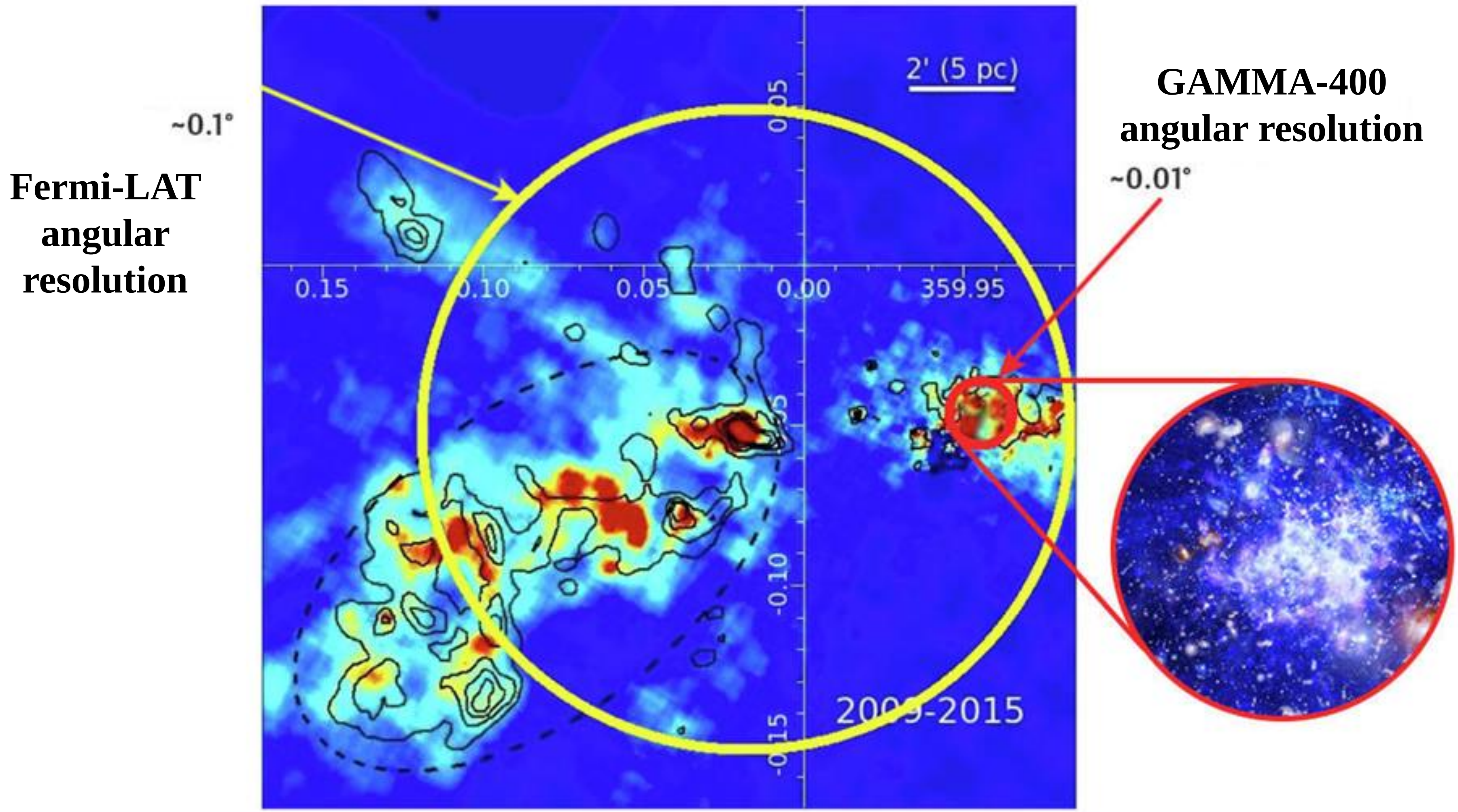
Studying gamma-ray emission from Galactic center, Galactic plane, Fermi bubbles, pulsar nebulae Crab, Vela, Geminga, Cygnus X complex, blazars, etc. with an aperture of ±45°



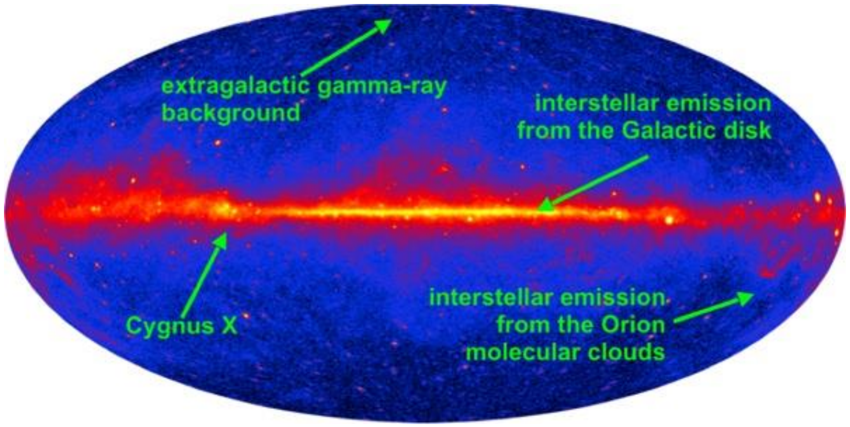
The figure shows that their main part of unassociated sources is located in the Galactic plane. Their identification requires high angular resolution - one of the tasks of GAMMA-400. In addition, according to the Fermi-LAT data, about 80 extended sources were found. Their mapping is a task for GAMMA-400. According to Fermi-LAT, there is an excess of gamma-ray emission at the Galactic Center, which can be explained either by the presence of dark matter or gamma-ray emission from millisecond pulsars - another challenge for GAMMA-400.



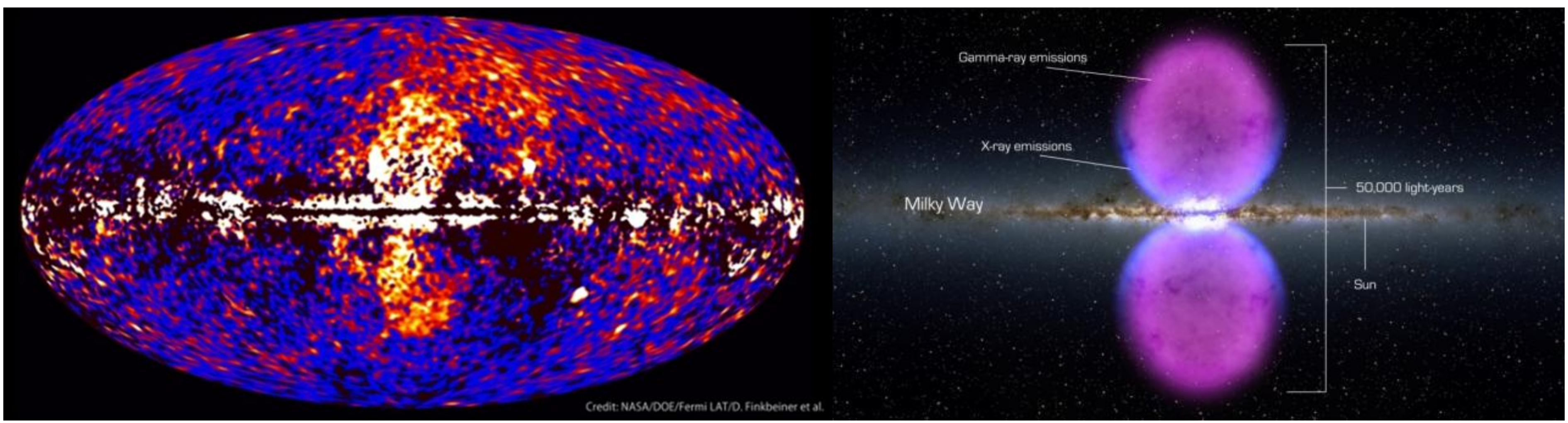
Studying the Galactic center.
Comparison of angular resolutions of Fermi-LAT (yellow) and GAMMA-400 (red) using X-ray observations of the Chandra telescope



Studying high-energy diffuse gamma-ray emission



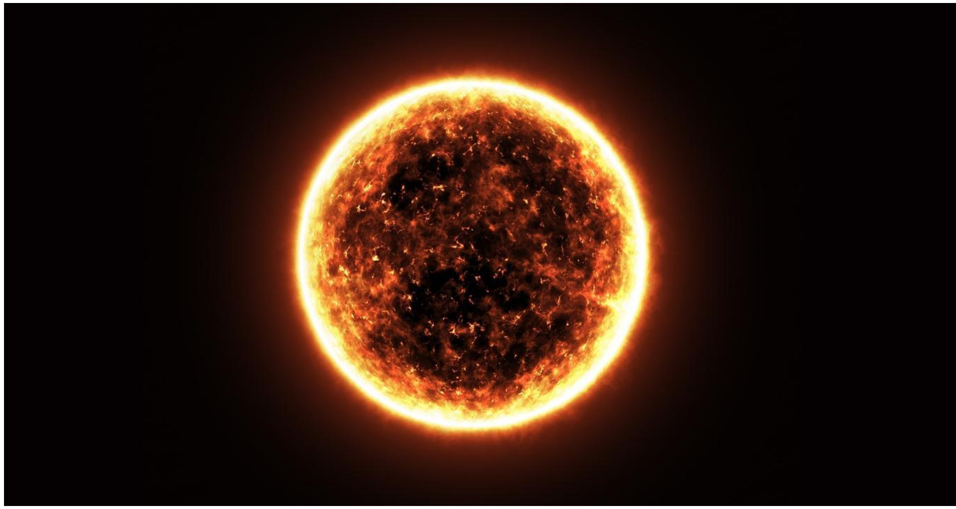
Fermi-LAT gamma-ray sky map and diffuse gamma-ray components: interstellar emission from the Galactic disk and extragalactic gamma-ray background.



Fermi bubbles

Additional experimental goals

Studying gamma-ray emission from the Sun in quiet time and during flares



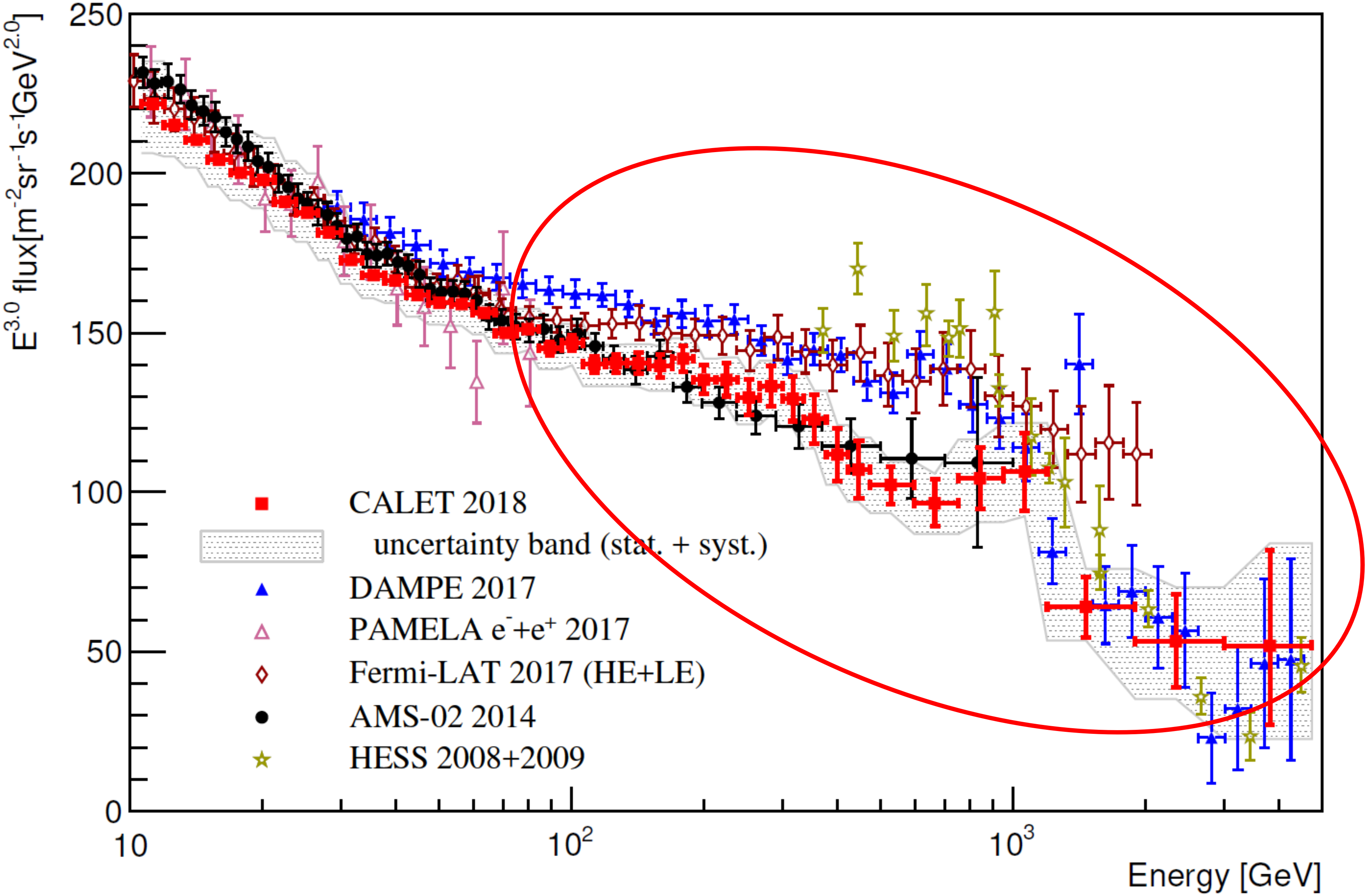
Searching for and studying gamma-ray bursts

GAMMA-400 will detect about 10 gamma-ray bursts per year in the main aperture in the energy range above 20 MeV and about 20 gamma-ray bursts per year in the lateral aperture in the energy range above 10 MeV.

Details in:

A. Leonov, et al., *Capabilities of the GAMMA-400 gamma-ray telescope to detect gamma-ray bursts from lateral directions, ASR, 69, 1, 514-530, 2022.*

Measurement of electron + positron fluxes in the range of 100 GeV - 20 TeV to refine the spectrum due to the high-energy resolution of the calorimeter with the thickness of 18-43 X_0 when detecting fluxes from top to bottom and from lateral directions



arXiv:1806.09728

Comparison of characteristics when detecting electrons + positrons for GAMMA-400 (top-down and for 4 lateral directions) with characteristics of Fermi-LAT, PAMELA, AMS-2, CALET, DAMPE

	GAMMA-400		Fermi-LAT	PAMELA	AMS-2	CALET	DAMPE
Aperture	top-down	4 sides	top-down	top-down	top-down	top-down	top-down
Acceptance, m^2 sr	~0.3	~0.5	2.5	0.02	0.4	0.1	0.3
Proton rejection factor	~10^4	~10^4	~10^4	~10^4	~10^4	10^5	10^5
Calorimeter area, m^2	0.7	4×0.24	0.85	0.06	0.42	0.1	0.36
Calorimeter thickness, X_0	18	43	8.6	16	16	30	32

Conclusions

- **After Fermi-LAT, the launch of the GAMMA-400 gamma-ray telescope in ~2030 presents a unique opportunity to significantly improve data on high-energy gamma-ray emission, high-energy electron and positron fluxes due to significantly better angular and energy resolution, large area, and long-term continuous observations.**
- **In addition, the simultaneous observations by an X-ray telescope and a gamma-ray telescope with the same angular resolution are of particular importance.**

GAMMA-400 website - http://gamma400.lebedev.ru/